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Evaluating the Effectiveness of Road Passage Structures for Freshwater Turtles in Massachusetts

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EVALUTATING THE EFFECTIVNESS OF ROAD PASSAGE STRUCTURES FOR FRESHWATER TURTLES IN MASSACHSUETTS

A Thesis Presented

by

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ABSTRACT

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Roads are long linear features on the landscape that impact wildlife and their habitats. Among all forms of wildlife turtles are one of the most negatively affected by roads. Wildlife biologists and civil engineers have developed and implemented road design measures to mitigate the negative effects associated with roads. One common approach used to reduce road mortality and to facilitate movement of turtles is to construct a road mitigation system. There are currently 28 road mitigation systems for wildlife in Massachusetts, of which 14 were specifically built for turtles. We identified all known systems in Massachusetts and collected site and structural design information for each. In addition, we also examined the relative effectiveness of experimental passages for freshwater turtles. Structures were evaluated with respect to how their height, width, and position (at or below-grade), influenced the movements of painted turtles. A total of 190 turtles were exposed to the experiential trials and their behavior was characterized by 3 response variables (Total time to complete the trial, Total hesitations observed, and Success based on no hesitations and completion of the trial in less than 120 minutes). We concluded that painted turtles exposed to below-grade tunnels were less hesitant and traveled faster through them as the tunnel size increased

from 0.6 m x 0.6 m to 1.2 m x 1.2 m. The 1.2 m x 1.2 m tunnel size overall proved to be the size with the fewest hesitations observed, fastest total times, and highest success rate.

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EVALUATION OF TURTLE ROAD MITIGATION SYSTEM CHARACTERISTICS IN MASSACHSUETTS

Introduction

Road Effects on Wildlife

Roads are long linear features on the landscape that impact wildlife and their habitats (Jackson 2000). In the United States there are over 6.5 million km of public roads that serve 247 million vehicles (USFHA 2007). The cumulative effects of these roads and their associated motor vehicle traffic are estimated to directly affect one-fifth of the land area of the continuous United States (Forman 2000). Road effects are positively associated with increased road densities, traffic volume, and traffic speeds (Forman et al. 2003). Wildlife cross roadways during their migration and dispersal across the landscape. The ecological effects of roads both directly and indirectly affect wildlife and their habitat (Jackson 2000, Trombulak & Frissell 2000). Direct effects include injury, mortality, alteration/restriction of movement/behavior, and loss of habitat (Jackson 2000, Forman et al. 2003). Indirect effects on wildlife include habitat fragmentation, degradation, isolation of wildlife populations, disruption of gene flow and metapopulation dynamics (Jackson 2000, Trombulak & Frissell 2000).

Vulnerability of Turtles

Among all forms of wildlife turtles are one of the most negatively affected by roads (Fahrig et al. 1995). They are a relatively slow moving and often have delayed reactions to motor vehicles on roadways. The life history strategies of freshwater turtles make them susceptible to the negative effects of roads (Mumme et al. 2000, Beaudry et al. 2008). Terrestrial movements of turtles include female migrations to nesting sites, dispersal of juveniles, movements among habitat patches, movement to escape unfavorable conditions, and movement of males to find mates (Gibbons 1986). Semi-terrestrial turtles such as the spotted (*Clemmys guttata*) and Blanding's (*Emydoidea blandingii*) turtles utilize a matrix of several, often small, wetland and upland habitats (Joyal et al. 2001). Overland migrations to these sites are often impeded by roadways, complicating their migrations (Joyal et al. 2001). These movements across the landscape can lead to road-associated injury and mortality.

Roadways and urbanization also influence movements by reducing habitat quality and spatially separating necessary resources (Budischak et al. 2006, Iglay et al. 2007). As a result, turtles are required to make longer movements to fulfill their biological needs (Marchand & Litvaitis 2004). Conservation of turtle species such as the Blanding's turtle is challenging due to these long overland movements, and the high rate at which their habitat is being fragmented by roads (Grgurovic & Sievert 2005).

The life history of turtles limits their ability to cope with additive mortality caused by roads (Congdon et al. 1993). Turtle life history is characterized by low annual recruitment rates, high adult survival rates, and delayed sexual maturity (Congdon et al. 1993, 1994). As a result, roads can lead to the alteration of the demographic and genetic structure of populations (Steen & Gibbs 2004, Beaudry et al 2008).

In some freshwater turtle populations, sex ratios have become male-biased as a result of female biased road mortality (Marchand & Litvaitis 2004, Steen & Gibbs 2004, and Aresco 2005). Females are often more vulnerable to road mortality because they make repeated nesting migrations, in addition to seasonal movements (Steen et al 2006). Gravid females exhibit strong nest site fidelity and will often move long distance to reach nesting areas (Obbard & Brooks 1980). Long migrations often cross roadways and sometimes shoulders of roadways are used for nesting, thus making the female susceptible to vehicular mortality, predation, and human collection (Ashley & Robinson 1996, Aresco 2004, Baldwin et al. 2004, Gibbs & Steen 2005). Gibbs & Steen (2005) attributed male-biased turtle populations to the expansion of the road network and determined that sex ratios near roadways increased from 45% to 60% male since the 1930's. These changes in the sex ratio of turtle populations may also serve as an indicator for their overall viability (Brooks et al. 1991).

Additive mortality due to roadways can lead to the decline of local turtle populations. Additive mortality of 2-3%, representative of rates caused by vehicle collisions, often leads to negative population growth rates for freshwater turtles (Gibbs & Shriver 2002). These levels of additive mortality are representative of what populations are experiencing along roadways in the eastern and central parts of the United States (Gibbs & Shriver 2002). Congdon et al. (1994) found that an increase in annual adult mortality of 10%, for common snapping turtles (*Chelydra serpentina*), would halve the number of adults in less than 20 years. Additive mortality due to road mortality in northeastern United States is believed to have caused the decline of spotted turtle (*Clemmys guttata*) and Blanding's turtle (*Emydoidea blandingii*) (Beaudry et al. 2008).

Mitigating Impacts of Roads on Turtles

Wildlife biologists and civil engineers have developed and implemented road design measures to mitigate the negative effects associated with roads. The goals of these measures are to reduce road mortality and facilitate movement across roadways (Jackson 2000). As our knowledge of installing road mitigation measures increases, the viability of affected populations will be enhanced through greater permeability across the landscape (Cramer & Bissonette 2005). Dedicated work will be required to insure consideration of mitigation systems in long-term highway planning, scheduled highway maintenance, and in the promotion of future research that determines if road mitigation is meeting the stated goals and objectives (Cramer & Bissonette 2005).

Often, these measures are designed for a single species or group of similar species (Jackson 2000). In North America most road mitigation projects are designed for large mammals (Jackson 2000). Mitigation techniques employed on roadways are fencing, underpasses, overpasses, warning signs, and lower speed limits (Forman et al. 2003, Dodd et al. 2004).

One common approach used to reduce road mortality and to facilitate movement of turtles is to construct a road mitigation system. A road mitigation system is a technique that can prevent wildlife from entering roadways (i.e. barrier fencing or structures), provide safe passage under roadways (i.e. tunnels, underpasses, overpasses), or any combination of these strategies. Properly designed and installed road mitigation systems can help minimize the impacts of roads on reptiles and amphibians (Aresco 2005).

Prior to the planning of a road mitigation system there should be sufficient evidence suggesting that there is a known population at risk (Jackson 2003). It is also necessary to identify a crossing point and document that the traffic volume represents a serious threat. Finally, the system needs to be accurately designed for the intended species and there must be a maintenance plan in place (Jackson 2003). In general, fencing can enhance the probability of the persistence of a population in areas of high traffic mortality by preventing wildlife from entering onto roadways and by funneling them to crossing structures (Jaeger & Fahrig 2004). If movement across a roadway is required to access a resource area, then a fence will never ensure the long term survival of a population unless coupled with a crossing structure (Jaeger & Fahrig 2004).

A study conducted in Paynes Prairie State Preserve, Florida, found that a barrier wall/culvert system reduced road mortality of reptiles and amphibians by 65%, and if tree frogs (*Hyla*) were not considered, then mortality rate was reduced by 93% (Dodd et al. 2004). Mortality rates were quantified by conducting pre and post-construction surveys at a site where a barrier wall/culvert system was installed (Dodd et al. 2004). Monitoring included road-kill and culvert surveys of eight culverts that pass under a 3.4 km stretch of US 441 (Dodd et al. 2004). A total of 2,411 (374 turtles) road-kills were recorded in the study area 12 months prior to installation and 158 (7 turtles) animals were killed during the post construction survey (Dodd et al. 2004). Culvert use increased tenfold after installation based on capture success (Dodd et al. 2004). Road mortality documented by the post construction survey was attributed to inadequate maintenance of the passage systems (Dodd et al. 2004). Build up of vegetation around, and gaps beneath, the barricade led to continued trespass of reptiles and amphibians onto US 441 (Dodd et al. 2004). Maintenance was also required to avoid build-up of debris and silt in the culverts (Dodd et al. 2004).

Similar success was found at Lake Jackson, Florida, where fencing reduced turtle mortalities by 98% through the redirection of turtles into pre-existing culverts (Aresco 2005). Turtle mortality before installation of the fence was (11.9/km/day) which was significantly greater than post-fence mortality (0.09/km/day) (Aresco 2005). Only 84 of

8,475 turtles climbed or penetrated the drift fences (Aresco 2005). Although vinyl erosion control fencing in combination with existing culverts is an inexpensive mitigation tool, annual replacement of fencing is required (Aresco 2005).

Boarman & Sazaki (1996) conducted a road-kill survey along two 24-km sections of highway (fenced and un-fenced) in the west Mojave Desert of California and monitored 3 culverts for use by desert tortoises (*Gopherus agassizii*) from 1992 to 1994. A relative comparison of the two sections of road concluded that there were 93% fewer tortoise road mortalities in the fenced section than the unfenced section. Mortality associated along the fenced area was attributed to gaps resulting from disrepair. In the first six months of monitoring, 2 tortoises used the culvert 10 times. Their level of monitoring did not allow them to determine if culvert use reduced the fragmenting effects of the road (Boarman & Sazaki 1996).

Hagood & Bartles (2008) monitored the use of existing culverts by eastern box turtles (*Terrapene carolina*). Volunteers installed 2.7 km of erosion control fencing along both sides of a 1.3 km section of road in Maryland. Two pre-existing drainage culverts were the means of safe road passage for turtles. Volunteers walked the fencing twice a day from 9 June to 31 October 2005 and monitored the culverts using cameras. Eighteen turtles were seen moving along the fence, and 3 (16%) of which were observed in the culverts. Prior to the installation of fencing (2004), 6 adult eastern box turtles were known to have been killed on the road, but none died following the installation of the fence (Hagood & Bartles 2008).

Based on several studies (Boarman & Sazaki 1996, Dodd et al. 2004, Aresco 2005, and Hagood & Bartles 2008), the utilization of existing drainage culverts as road passage structures, and the installation of temporary fencing, can reduce road mortality. Mitigation structures need to be continuously maintained and repaired in order to help insure their continued use and effectiveness (Cramer & Bissonette 2005).

Road Mitigation Systems in Massachusetts

Turtle road mitigation systems in Massachusetts are constructed as a means of reducing road mortality and habitat fragmentation. There are 10 species of terrestrial and aquatic turtles in Massachusetts, of which 6 are protected under the Massachusetts Endangered Species Act.

The Massachusetts Endangered Species Act (MESA) (M.G.L c.131A) and its implementing regulations (321 CMR 10.00), seeks to protect state-listed rare species and their habitat. MESA was signed into law by Governor Dukakis on December 27, 1990 (Chapter 408 of the Acts of 1990). It became effective on March 27, 1991. The MESA regulations became effective upon publication on January 31, 1992. MESA and its implementing regulations protect rare species and their habitat by prohibiting the "Take" of any plant or animal species listed as Endangered, Threatened, or Special Concern by the Massachusetts Division of Fisheries and Wildlife-Natural Heritage and Endangered Species Program (NHESP). "Take is defined as to harass, harm, pursue, hunt, shoot, hound, kill, trap, capture, collect, process, disrupt the nesting, breeding, feeding or migratory activity or attempt to engage in any such conduct, or to assist such conduct, and in reference to plants, means to collect, pick, kill, transplant, cut or process or attempt to engage or to assist in any such conduct. Further, the regulations specify that disruption of nesting, breeding, feeding or migratory activity may result from, but is not limited to, the modification, degradation or destruction of habitat (321 CMR 10.00)". Projects resulting in a "take" of state-listed rare species may be eligible for a Conservation and Management Permit (CMP) (321 CMR 10.23). A proponent must design and implement a CMP that provides a long-term Net Benefit to the conservation of the affected state-listed species (321 CMR 10.23).

The installation of a turtle road mitigation system has been used as a conservation technique to provide the long term Net Benefit when state-listed turtle species were likely to be affected by development projects in Massachusetts. However, road mitigation systems are expensive and not guaranteed to work (Mata et al. 2008). Factors such as animal behavior, the size of the passage structure, placement on the landscape, and population structure all affect the system's success (Jackson & Griffin 2000). With very little scientific literature available on road mitigation system design, engineering is often left up to best professional judgment and anecdotal evidence. Currently, only a few systems have been monitored for their effectiveness in Massachusetts, but this information is paramount in order to determine if NHESP's current passage design standards are effective.

The goal of our study was to evaluate turtle road mitigation system characteristics in Massachusetts. We identified all known systems in Massachusetts and documented their structural design, and, where possible, their effectiveness. This information will provide a basis for understanding how various design characteristics affect mitigation success, a critical step before meaningful design standards can be developed. We also described the geographic distribution of the structures and their timing of installation.

Methods

Data Collection

We identified road mitigation systems and their locations in Massachusetts by contacting the state's transportation departments (Massachusetts Highway Department and Massachusetts Turnpike Authority), wildlife agency (Massachusetts Division of Fisheries and Wildlife and NHESP program), environmental consulting firms that practice in the state, municipal conservation agents, and experts in the field of road ecology. Results are reported here only for road mitigation systems designed specifically for turtles.

Site Analysis

During the interview process we collected information on site characteristics, structural design, maintenance, and monitoring of existing road mitigation systems in Massachusetts. A road mitigation system in this study is defined as a technique that can prevent wildlife from entering roadways (i.e. barrier fencing or structures), provide safe passage across roadways (i.e. tunnels, underpasses, overpasses), or any combination of these strategies.

Site characteristics collected were location (street address), type of associated development (residential, commercial, and governmental (municipal, state, federal roadways)), number of lanes on the road, reason for installation and date of construction. Structural design information gathered included number of tunnels, tunnel dimensions (height , width , length), tunnel position relative to the surrounding landscape (at or below-grade), substrate within tunnels, whether the tunnel had an open top design (lighting), presence of barrier fencing, fencing height, fencing embededness, and fence construction material. Interviewees were also asked about the cost of the project, whether monitoring was conducted, and if so, the success of the mitigation system.

Every road mitigation site was visited in order to collect site specific data and confirm information provided in the interviews. Data were analyzed using Microsoft Excel (2003).

Estimated Material Cost of Mitigation Systems

In order to improve our cost estimates, we gathered additional information on costs of materials by contacting construction supply companies in Massachusetts. These values were then used to produce a table of 2008 costs for the most common structural materials.

Results

Site Characteristics

We identified 28 sites with road mitigation systems for wildlife in Massachusetts, of which half (14) were specifically built for the passage of turtles (Table 1) (Appendix). The remaining 14 systems were constructed either for amphibians (3) or wildlife in general (11). The first turtle system in Massachusetts was constructed in 2000, with the number of systems constructed increasing in recent years (Figure 1). In addition to the 14 existing turtle mitigation systems, six additional systems are in the process of being constructed. The six systems being built are all the result of MESA and the issuance of a CMP, as are 11 of the 14 turtle systems that have been constructed. The remaining 3 constructed systems are in place because of a town's requirement or request (2), or a volunteer effort from the local community (1). Every turtle road mitigation system has been built with the intention of protecting a state-listed species under the Massachusetts Endangered Species Act. Geographically, these passage systems are either found in suburban areas near Boston or within the Connecticut River Valley (Figure 2). Turtle passage systems were constructed for development projects classified as governmental (federal, state, municipal roadway) (5), residential (6), or commercial (3) (Table 1).

Structural Design of Road Mitigation Systems

Six of the ten sites with mitigation systems had passage structures designed to utilize box culverts with a natural substrate. All of these structures were made out of pre-cast concrete and placed at-grade with the surrounding landscape, with only 2 of 10 sites having an open top design to provide overhead lighting. Six of the 10 sites with passage structures consisted of only 1 tunnel. The mean (Standard Deviation (SD)) (range) height, width, and length of the passage tunnels were: 1.5 m (1.2) (0.2 m - 4.6 m), 6.5 m (14.1) (0.4 m – 61 m), and 20.9 m (20.1) (3.7 m – 91.4 m), respectively (Table 1). Four (Gill, Carver, Southampton, Westford) of the ten sites with turtle passages structures were also designed to include a pre-existing stream channel. This design is intended to allow turtles to retain established movement patterns within the pre-existing stream channel.

Nine of the fourteen mitigation systems incorporated barrier fencing into their design. Four of the nine mitigation systems only incorporated fencing, no tunnels. Four of the nine systems that incorporated fencing utilized chain link, embedded in the soil, and had smaller chain link or wire mesh attached to prevent turtles from escaping through or under the fence. Mean (SD) (range) fence height was 0.9 m (0.6) (0.2 m – 1.8 m).

Two of the nine systems incorporated fencing in combination with an open-topped tunnel. Open top designs placed storm grates placed end to end on the top of pre-casted box culverts to increase light entering the tunnel. Storm grates 0.6 m x 1.2 m in size were placed in the center of the driving lanes and at the edges of the road to reduce vehicular traffic directly on the grates.

Maintenance and Monitoring of Road Mitigation Systems

None of the 14 sites showed evidence of maintenance beyond landscape aesthetics. Maintenance is one of the biggest problems associated with the long-term effectiveness of road mitigation systems (Compton & Sievert 2002). Conservation Management Plans require maintenance, though this requirement is difficult to enforce. Consistent follow-up must be implemented. Interviewees reported monitoring of their road mitigation systems at six of the 14 sites. Four of the six monitored sites had road passage tunnels (Carver, Boxborough, Westford, and Hingham); the other two were fence only systems (Table 1). Monitoring ranged from radio-telemetry and thread bobbin movement data to visual observations. The Carver site was the only one of the six sites which reported their findings in conference proceedings or scientific journal (Kaye et al. 2005). The remaining 5 sites reported their findings to NHESP (Table 1). It is unknown whether systems showing evidence of use were necessarily effective in maintaining viable populations of the target species.

Estimated Material Costs of Mitigation Systems

We estimated the cost of common structural material associated with road mitigation systems, but were unable to determine the total project cost for any of the 14 sites. As the scale of a tunnel's length, height, width, and lighting increased, the individual material costs increased exponentially (Table 2 & 3). As the length of fencing increased and the link size decreased, the overall fencing cost increased (Table 3). Fencing material cost was higher for concrete curbing, compared to chain-link (Table 3).

This is not clearly represented in Table 3 because we were unable to obtain the material cost for chain-link fencing independent of installation. The companies surveyed would not quote the material cost of chain-link alone. The estimated material costs for a 0.6 m x 0.6 m (height x width) and a 0.6 m x 1.2 m (height x width) storm grate and frame (light window) is $280.00 and $450.00, respectively.

We generated two material cost estimates for a two-lane road mitigation system. Both options require 12 m of tunnel, six 0.6 m x 1.2 m storm grates for lighting, and 914 m of 0.5 m high concrete curbing. The passage structure material in Option 1 will be a 4 sided box culvert and in Option 2 is a corrugated circular pipe. The combined material cost for Option 1 was $35,210.00 and for Option 2 was $51,348.00. Increases in the number of passage structures, fencing length, material type, and lighting will raise the overall material cost of a road mitigation system.

Discussion

Road Mitigation Systems in Massachusetts

Turtle mitigation systems were first constructed in Massachusetts in 2000 in response to modifications of environmental regulations. In 1995, amendments to the Massachusetts Endangered Species Act streamlined the review process of projects in priority habitat as well as defined the regulatory authority of the Natural Heritage and Endangered Species Program (J. Regosin pers. comm.). Increased NHESP staffing in the late 1990's and better mapping software allowed NHESP to more accurately map Element Occurrences, Priority Habitat, and Estimated Habitat (J. Regosin pers. comm.). An Element Occurrence is a geographically distinct record of a single or multiple observation of a state-listed listed species, documented in the NHESP database (NHESP

2009). With more of the state mapped for Priority Habitat, the probability of a project requiring a review increased, thus leading to potential road mitigation. However, NHESP prefers to alter the design of a proposed project to avoid any potential take of a state-listed species, thus avoiding a CMP and the need for a road mitigation system (J. Regosin pers. comm.). In addition, some local communities and conservation groups became interested in the creation of these systems, in circumstances where they were not required by NHESP.

Road mitigation systems in Massachusetts typically have one or more tunnels with a natural bottom substrate. The number of tunnels and tunnel size varied with site conditions (size of the road, traffic volume and extent of affected area). Number of lanes, presence of sidewalks or median strip would increase the length of the tunnel. Road effects are positively associated with increased road densities, traffic volume, and traffic speeds (Forman et al. 2003). Roads with high traffic speeds and volumes should require additional tunnels and or fencing to offset the negative road effects (habitat fragmentation and degradation, as well as direct road mortality). In the design of wildlife mitigation systems with tunnels, NHESP recommends the largest tunnel dimensions financially and structurally possible (J. Regosin pers. comm.). Site specific conditions, such as rocky terrain and high water table issues, can limit the physical size of passage structures. If one did not reduce the size of the tunnel, these site effects on tunnel size would increase the financial cost of a project because a larger amount of excavation or fill would be required to place the passage under the road. Open top designs are strongly recommended by NHESP, especially when passage dimensions are limited by site specific characteristics (J. Regosin pers. comm.). Unfortunately some municipalities and

MassHighway feel that the grated open tops are a safety hazard, especially to cyclists. No open top design in Massachusetts has proven to be a safety hazard. Fencing is expected to span the length of the area of rare species habitat to be impacted because NHESP does not want the state-listed species to enter the roadway (J. Regosin pers. comm.).

Due to the lack of information available on design of turtle mitigation systems, adaptive design and professional judgment commonly are a critical part of the system design. One opportunity for adaptive design is to learn from the use of embedded corrugated PVC for turtle barriers as found at the Westford and New Bedford, MA, sites. These designs were judged to be ineffective for the long-term conservation of the affected species because of their height and the upkeep required to prevent the overgrowth of vegetation from breaching the barrier. There is no evidence of funding sources available to correct failed road mitigation systems. Any historic design considered to be ineffective will not be implemented on future systems. This has led to the preference for chain link fences as turtle barriers. Ultimately, finding a biologically effective and cost efficient road mitigation system is the goal of NHESP (J. Regosin pers. comm.). Anecdotal evidence from existing systems has provided us with a few cases in which future design recommendations can be based.

There is evidence to suggest that the Westfield fence system is preventing eastern box turtles (*Terrapene carolina*) from getting into a commercial area because of construction monitoring and a local radio-telemetry study conducted by Liz Willey. The Westfield fence system is a 0.4 m high concrete curb around a commercial area, physically preventing eastern box turtles from entering the area. A fundamental problem with the system is that if a turtle follows the curb to the end, it comes in contact with a road. The design of the curb is an effective barrier for box turtles; however, the layout of the system places turtles in danger. This is a common problem with site based mitigation structures. This problem can be potentially corrected in future designs by turning the end of the fencing system back away from the road (Aresco 2005, Hagood & Bartles 2008).

Passage system monitoring has also indicated that spotted turtles (*Clemmys guttata*) are using the specially designed train track baffles at the site in Hingham, a large arch culvert in Westford, and a 1.8 m x 1.8 m box culvert in Carver. The Hingham site utilizes 42 train track baffles with fencing to direct spotted turtles underneath a commuter rail line. This system prevents turtles from getting killed on the tracks and has safely passed turtles beneath the rails. Long-term monitoring or population modeling is required to determine if it passes enough individuals to insure the long term conservation of the local population. The Westford site utilizes a large arch culvert and fencing to connect habitat and allow turtles to safely pass underneath a residential road. The tunnel spans a pre-existing stream channel and upland banks. The scale of the Westford tunnel is such that white-tailed deer (*Odocoileus virginianus)* and people have been documented passing through it. Based on the scale of the system and anecdotal evidence of use, it is considered a successful design. It has the potential to remain effective as long as the associated fencing prevents turtles from entering the roadway.

Kaye et al. (2005) monitored the use of a 1.8 m x 1.8 m box culvert by spotted turtles at the site in Carver. They used radio telemetry, thread-tracking, and visual observations to monitor the use of the culvert and the surrounding landscape (Kaye et al. 2005). Kaye et al. (2005) found direct use of the culvert by seven spotted turtles through thread trails and observations of individuals passing through the tunnel (Kaye et al. 2005). Indirectly, they inferred use of the tunnel by 13 individuals based on the movement data measure using radio telemetry (Kaye et al. 2005). Three turtles were observed at the entrance of the culvert; however, they were never documented using the passage or found on the other side of it (Kaye et al 2005). In their judgment the passage system proved successful because it passed turtles (Kaye et al. 2005).

The Carver system was constructed as a part of a CMP. The objective of a CMP is to ensure the long term conservation of the affected species using on or offsite mitigation. Radio telemetry alone provides little information about structure use, but is useful to determine the extent that the roadway inhibits wildlife movement (Jackson 2000). Direct observations and the use of thread tracking documented the use of the tunnel. Using all of these techniques allows one to evaluate the degree to which the passage system is mitigating the effects of the road on animal movement (Jackson 2000). This system, like all of the other road mitigation systems in Massachusetts, lacks information about their long term conservation value.

A passage structure in Boxborough has proven to be ineffective for Blanding's turtles (*Emydoidea blandingii*) passage by a group of researchers from the University of Massachusetts, Amherst (Compton & Sievert 2002). Their monitoring efforts documented the use of one of the three 4.6 m x 17.1 m open-top, 3-sided box culverts by a painted turtle (*Chrysemys picta*). They cited design of the passage entrances as the cause of the ineffectiveness (Compton & Sievert 2002). The manner in which the curbs and the entrances of the tunnels connected tended to direct turtles away from the passage structure. Researchers cited that one of the biggest problems is the maintenance of the curb, mainly because of its low height. Over time, the curb became compromised by trash, vegetation, and other debris (Compton & Sievert 2002). A breach of the curb would allow turtles to enter the roadway. Compton and Sievert (2002) felt that a curb must be higher than 0.2 m to prevent crossing by Blanding's and painted turtles.

Estimated Material Costs of Mitigation Systems

We were unable to collect information on the cost of installing a system since any information pertaining to cost of construction would only be available from the developer or contractor and not the consultant or state agency. However, we did estimate the cost of materials (Table 2 & 3) allowed us to examine how scale of the project affects cost. Material costs increase as size and openness of the tunnel increases. One way of reducing cost is to use 3-sided box culverts with a natural substrate for the floor. Using a 3-sided box culvert, rather than a 4-sided one provides a savings of $148.00 per meter for a 1.2 m x 1.2 m culvert.

Conclusions

There are relatively few sites with road mitigation systems specifically designed for turtles in Massachusetts; however, no other study has this many documented turtle systems. These systems are commonly associated with residential two-lane roads in eastern Massachusetts and the Connecticut River Valley. Structurally these systems tend to be a box culvert type passages which are connected to chain-link fencing. They are typically built and not maintained, thus jeopardizing their long-term effectiveness (Compton & Sievert 2002). Thus far, monitoring has been minimal, preventing a rigorous evaluation of their effectiveness in safely passing turtles under roads, and thus conserving local populations.

Management Implications

The information gathered from this study provides a database of case studies for turtle road mitigation systems in Massachusetts. These case studies will allow biologists to reference local mitigation techniques that can assist in the design of future systems. We were able to make structural design recommendations from the small amount of monitoring information from these case studies. Based on the information gathered we suggest that tunnels be installed at-grade where possible, with a natural bottom, open top, and minimum tunnel dimensions of 1.2 m x 1.2 m. Monitoring of turtle curbing and fencing at the Westfield and Boxborough sites suggest that fencing should be higher than 0.2 m height and should be embedded. Embedding fences will help prevent turtles from going under them. It is also important to realize the need for maintenance of these systems, as documented at the New Bedford, Westford, and Boxborough sites. Both concrete curbing and chain link fencing have an average lifespan of 20 years. If debris and vegetation are not cleared from around the fencing, then it creates the potential for turtles to circumvent the barrier. It was observed at the Carver and Harvard sites that chain link over time tended to curl up creating a gap at the bottom of the fence big enough for some wildlife to pass. Concrete curbing maintained its form and did not bend/break when struck by falling tree limbs as compared to chain link fencing at the Carver site.

Future Research

We urge further research on road mitigation system design as it pertains to turtle behavior. Understanding how the structural design of these system affect the willingness of turtles to use them will allow us to better facilitate turtle passage and directly develop future design recommendation (Woltz et al. 2008). Additional research is required to assess the long term conservation concerns. Are the road mitigation systems reducing road mortality enough to maintain a population over long time periods? Does the system maintain a connection to high quality habitat? Does the system create a barrier effect? Monitoring of existing structures will provide biologists with an assessment of the current passage designs, and an evaluation of their effectiveness as a conservation tool. Cramer & Bissonette (2005) suggest that structures be monitored for at least three years after construction because it may take wildlife two or more years to adapt. Ultimately, these bigger conservation questions need to be addressed in order to support the future construction of road mitigation systems (Forman et al. 2003, Dodd et al. 2004).

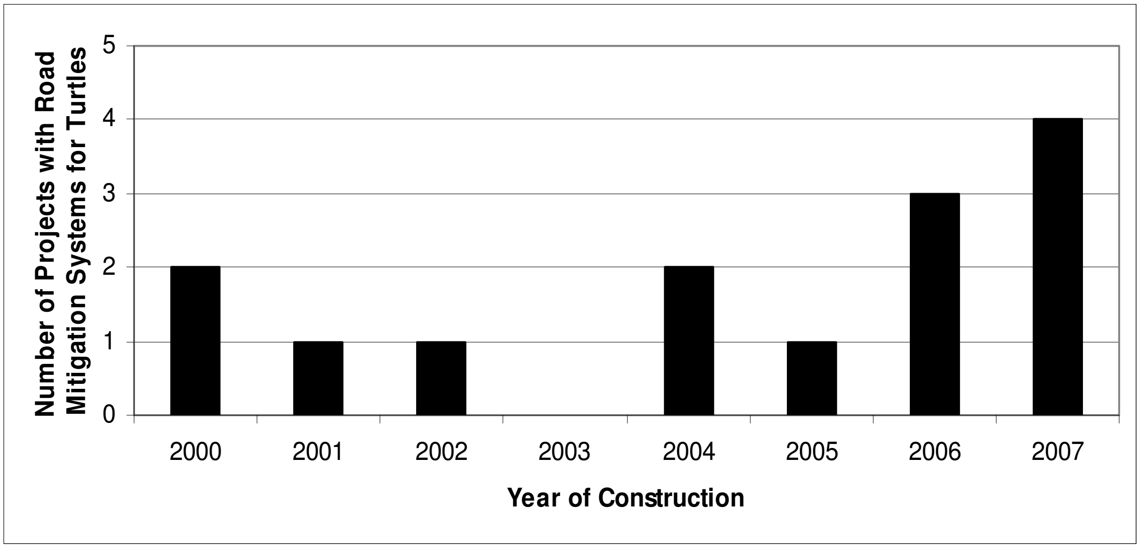


Figure 1: Annual variation in the number of turtle road mitigation systems constructed in Massachusetts.

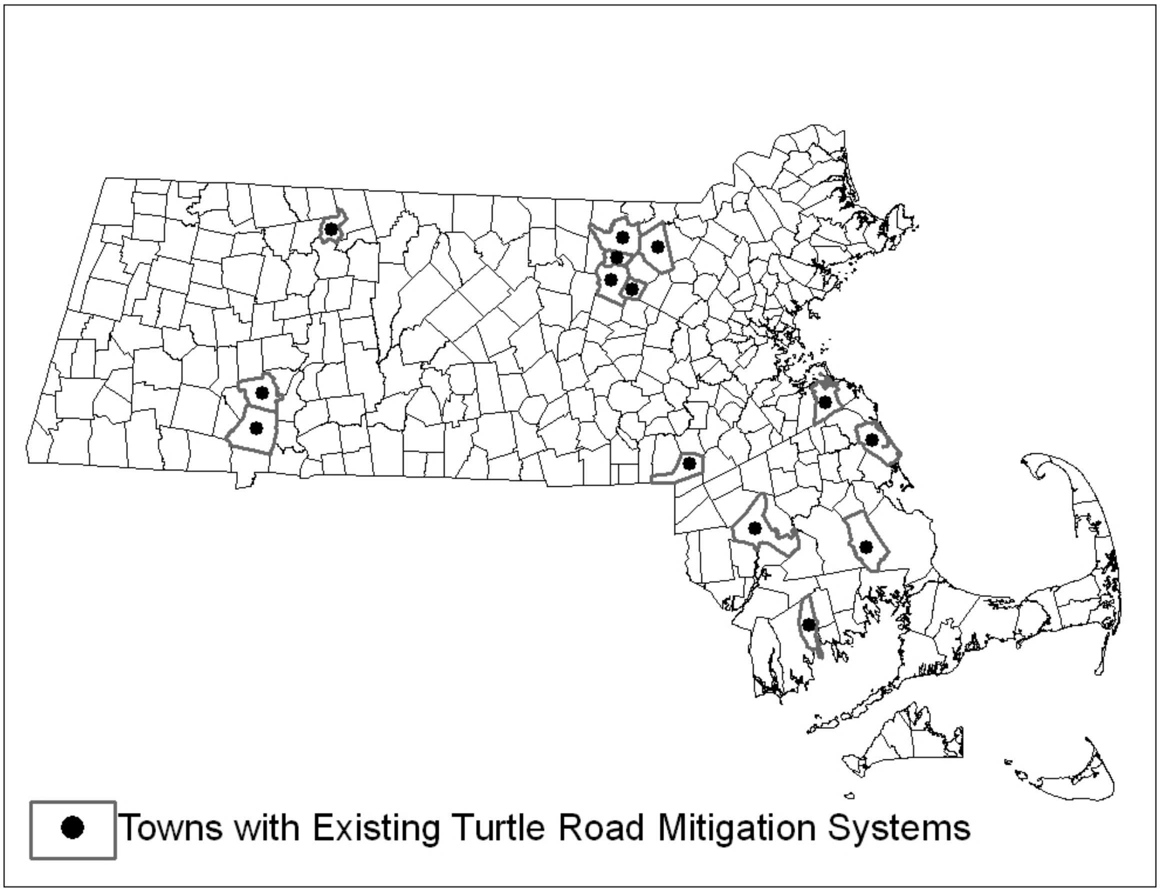


Figure 2: Distribution of road mitigation systems, specifically designed for turtles in Massachusetts.

Table 1: Characteristics of site, passage, and fencing at 14 sites in Massachusetts that have turtle road mitigation systems.

Site					Passage								Fence				
Location	Development	Reason	Date	# of Lanes	Passage Design	#	Height (m)	Width (m)	Length (m)	Position At or Below	Open Top	Substrate	Fence	Height (m)	Embedded	Monitoring	Evidence of Use
Carver	Governmental	MESA	2004	2, 4	Box Culvert Bridge Span	2	1.8, 4.6	1.8 61	16.8, 91.4	At	No	Natural	Yes	1.8	No	Yes	Yes
Groton	Residential	MESA	2005	2	N/A	0	N/A	N/A	N/A	At	N/A	N/A	Yes	0.6	Yes	No	Unknown
Taunton	Governmental	MESA	2000	2	Box Culvert	1	0.3	0.5	16.2	At	No	Concrete	No	N/A	N/A	No	Unknown
Westfield	Commercial	MESA	2006	2	N/A	0	N/A	N/A	N/A	At	N/A	N/A	Yes	0.4	Yes	Yes	Yes
Gill	Governmental	Town	2007	2	Box Culvert	1	1.8	2.4	15.6	At	No	Natural	No	N/A	N/A	No	Unknown
New Bedford	Commercial	MESA	2004	2	N/A	0	N/A	N/A	N/A	At	N/A	N/A	Yes	0.6	Yes	No	Unknown
Marshfield	Residential	MESA	2002	2	Squash Pipe	2	0.4	0.4	24.7	At	No	Concrete	No	N/A	N/A	No	Unknown
Wrentham	Residential	Town	2006	2	Corrugated Pipe	1	2.1	2.1	49.1	At	No	Metal	No	N/A	N/A	No	Unknown
Southampton	Residential	MESA	2007	2	Arch Culvert	1	3.4	14.6	12.5	At	No	Natural	No	N/A	N/A	No	Unknown
Harvard	Governmental	Volunteer	2007	4	N/A	0	N/A	N/A	N/A	At	N/A	N/A	Yes	1.8	No	Yes	Yes
Westford	Residential	MESA	2001	2	Arch Culvert	1	3.4	11	12.2	At	No	Natural	Yes	1.2 0.3	Yes	Yes	Yes
Ayer	Residential	MESA	2006	2	Box Culvert	1	1.2	3.7	15.2	At	Yes	Natural	Yes	0.6	Yes	No	Unknown
Boxborough	Commercial	MESA	2000	2	Box Culvert	3	0.9	4.6	17.1	At	Yes	Natural	Yes	0.2	Yes	Yes	Yes
Hingham	Governmental	MESA	2007	0	A)Box Culvert B)Squash Pipe C)Baffle	A)2 B)1 C)42	A)0.9 B)1.2 C)0.2	A)0.9 B)1.8 C)0.4	A)8.2 B)10.1 C)3.7	At	No	Natural	Yes	A)1.8 B0.9 C)0.3	Yes	Yes	A)Unknown B)Unknown C)Yes

Table 2: Estimated material cost ($/m) of passage designs in Massachusetts based on structure type, material, and dimension.

Passage Design Type	Material	Passage Dimensions: Height x Width (m) 1.2 x 1.2	2.4 x 2.4	3.7 x 3.7
Circular Culvert	Corrugated Metal	138.00	374.00	607.00
3-Sided Box Culvert	Concrete	394.00	1246.00	2772.00
4-Sided Box Culvert	Concrete	541.00	1689.00	3805.00

Table 3: Estimated material cost ($/m) of fence designs in Massachusetts based on structure type, material, and height.

Fence Design Type	Material	Height (m)	Cost per (m)
Link Fence (0.05 m link)	Galvanized chain link	1.2	43.00 (installed)
Link Fence (0.03 m link)	Galvanized chain link	1.2	49.00 (installed)
Curbing	Pre-cast Concrete	0.5	30.00

CHAPTER 2

AN EXPERIMENTAL TEST OF TUNNEL SIZE AND POSITION ON PASSAGE OF PAINTED TURTLES (*CHRYSEMYS PICTA*)

Introduction

Turtles and Roads

Roads are major features on the landscape that impose an array of ecological effects (Jochimsen et al. 2004). Turtles often encounter roads when they move across the landscape (Mumme et al. 2000, Beaudry et al. 2008). Many species undertake terrestrial movements, including migrations to nesting sites, dispersal of juveniles, movement to escape unfavorable conditions, and movement of males to find mates (Gibbons 1986). Overland movements are often disrupted by roadways, complicating turtle migrations (Joyal et al. 2001). Roads directly and indirectly affect turtles and turtle populations (Jackson 2000, Trombulak & Frissell 2000). Direct effects include injury, mortality, alteration/restriction of movement/behavior, and loss of habitat (Jackson 2000, Forman et al. 2003). Indirect effects include habitat fragmentation and degradation, isolation of turtle populations, disruption of gene flow and metapopulation dynamics (Jackson 2000, Trombulak & Frissell 2000). The negative impacts these effects have on populations are correlated with increased road densities, traffic volume, and traffic speeds (Forman et al. 2003). Roads can also lead to an increase in collection and intentional killing of turtles (Ashley et al. 2007).

Turtle populations are extremely vulnerable to adult road mortality because their life history includes low annual recruitment, high adult survival, and delayed sexual maturity (Congdon et al. 1993, 1994). As a result, they are limited in their ability to cope with the additive mortality associated with environmental disturbances such as roads

(Congdon et al. 1993). The reduction in habitat quality and size coupled with additive road mortality can alter the demographic and genetic structure of populations (Steen & Gibbs 2004, Beaudry et al 2008). There is evidence that sex ratios of freshwater turtle populations in some areas have become male-biased as a result of higher road densities and their associated road effects (Marchand & Litvaitis 2004, Steen & Gibbs 2004, and Aresco 2005). Females are most vulnerable to road mortality because of their repeated nesting migrations that occur in addition to seasonal movements (Steen et al 2006). These long migrations often cross roadways and can lead them to open shoulders of roads that offer favorable nesting conditions that may attract nesting females. Such close proximity to roads makes them susceptible to mortality, predation, and human collection (Ashley & Robinson 1996, Aresco 2005, Baldwin et al. 2004, Gibbs & Steen 2005).

If the additive mortality resulting from roadways is too great, then local turtle populations are at risk of decline. A 2-3% additive mortality caused by vehicle collisions is suspected to be more than most turtle populations can withstand and still maintain positive population growth rates (Gibbs & Shriver 2002). Congdon et al. (1994) found that an increase in annual mortality of 10% of adult common snapping turtles (*Chelydra serpentina*) would halve the number of adults in less than 20 years. It is suspected that the cumulative effects of roads have led turtle species such as the spotted turtle (*Clemmys guttata*) and Blanding's turtle (*Emydoidea blandingii*) to decline throughout much of their range in the northeastern United States (Beaudry et al. 2008).

Mitigation

State and federal transportation agencies, with the help of biologists, are making efforts to reduce the effects of roads on turtles and other wildlife. Several measures have been and can be implemented to prevent and mitigate the effects of roads on amphibians and reptiles (Jochimsen et al. 2004). Mitigation techniques fall into two categories: techniques that affect motorist behavior (lower speed limits and signs) and those that influence animal behavior (fencing, crossing structures and habitat modification) (Forman et al. 2003, Dodd et al. 2004). The function of passage structures is to get animals safely across a roadway, thereby facilitating natural movements and usually reducing road mortality (Forman et al. 2003). Habitat modification and fencing can prevent wildlife from getting onto roadways and help to channel wildlife to designated crossing locations (Forman et al. 2003). Location of passage structures on the landscape is important (Yanes et al. 1995, Jackson & Griffin 2000, and Clevenger & Waltho 2000), and they are most effective where crossing points in conjunction with high traffic have been identified (Jackson 2003).

Measures of Success

There are a variety of mitigation passage designs in use, having differing levels of success (Forman et al. 2003). Factors influencing success include: the structural design of the passage, surrounding landscape features, and the level of human activity near the structure (Yanes et al. 1995, Clevenger & Waltho 2000). The main goals of passage structures are to reduce road mortality and facilitate movement across roadways (Jackson 2000). Most attempts to evaluate the success of crossing structures focus exclusively on documenting use of structures (Forman et al. 2003). This measure of success, however, can be interpreted in both absolute and relative terms. A successful passage structure (in relative terms) should have more crossings through it than successful or attempted crossings over the road surface by the targeted species (Bellis et al 2009). The absolute measure of a mitigation project should fulfill its conservation goals. Does the project reduce road mortality, connect habitat, and allow for migration and dispersal? Is it enough to offset the effects of the road on the local population? Forman et al. 2003 recommend six measures to determine the effectiveness of road passage structures: (1) reduction in road mortality rates post-mitigation; (2) maintenance of habitat connectivity; (3) maintenance of genetic interchange; (4) fulfillment of biological requirements; (5) dispersal and recolonization; (6) maintenance of metapopulation and ecosystem processes. It is financially and logistically difficult to determine the absolute success at this scale for every project. The cost of installing and monitoring road crossing structures are substantial (Mata et al 2008). The above conservation questions, however, still need to be addressed in order to support the future construction of road mitigation systems (Forman et al. 2003, Dodd et al. 2004).

The appropriate strategy is to understand the effectiveness of existing mitigation projects and make adaptive changes to designs and planning as additional knowledge becomes available (Jackson & Griffin 2000). This will allow us to identify practical and functional strategies necessary to mitigate the impacts that roads have on wildlife (Jackson & Griffin 2000).

Properly designed and installed crossing structures coupled with fencing have been shown to reduce the affects of roads on reptiles and amphibians (Dodd et al. 2004, Aresco 2005). Reduced rates of road mortality have been observed post-mitigation and habitat connectivity was provided through use of culverts (Dodd et al. 2004, Aresco 2005). Dodd et al. 2004 reported a total of 2,411 (374 turtles) road-kills recorded in the study area 12 months prior to the installation of a barrier-wall-culvert system and 158 (7 turtles) animals killed during the post construction survey (Dodd et al. 2004). Aresco (2005) found that the rate of turtle mortality went from 11.9/km/day before installation of the fence to 0.09/km/day post-construction of a barrier fencing system. In the Lake Jackson system turtles used a 3.5 m diameter culvert in which light was visible from each side and had a natural sand/silt substrate (Aresco 2005). Dodd et al. (2004) recorded the use of 0.9 m, 1.8 m x 1.8 m, and 2.7 m x 2.7 m culverts by turtles. Hagood & Bartles (2008) documented the use of 0.5 m drainage culvert as a passage structure when in conjunction with temporary fencing. However, information from the available studies on a variety of species in different ecological settings provides little in the way of guidance for those designing future mitigation projects.

Mitigation Designs and Behavior

The case studies discussed above vary in their scale, complexity, and measured success in reducing road effects for turtles. In addition to the comparison of case studies, further research is required to determine how structural design elements affect their behavior (Compton & Sievert 2002, Griffin 2005, Smith et al. 2005, and Woltz et al. 2008). Proper design of these structures requires a strong understanding of the target species behavior (Forman et al. 2003). Inadequate consideration of behavior in the design of passage structures can lead to complete avoidance and utilization of a structure by the target species (Pucky 2003).

Currently, there are very few studies that have evaluated the factors affecting passage use by reptiles (Jochimsen et al. 2004). Ruby et al. (1994) looked at the behavioral responses of captive desert tortoises (*Gopherus agassizii*) to different types of barriers and barrier material. Tortoises were placed in thirteen 4.6 m x 4.6 m square pens and were presented with a different barrier in each. Individuals were first tested in each barrier pen for 30 minutes to measure their initial response, followed by 2 hours and then overnight (Ruby et al. 1994). Data were collected on the number of approaches to the barrier, total time the animal was in body length distance and the type and number of contacts with the barrier. Finally, they placed tortoises 2-3 m from an existing highway barrier and culvert, and documented their behavior. Their tests suggest that a screen mesh with small enough openings to exclude a tortoise's head was the most suitable barrier material. Tortoises did not have a preference to follow a solid or mesh fencing, willingly entered culverts under large highways (Ruby et al. 1994).

Jackson and Marchand (1998) conducted a study looking at the use of a prototype tunnel by painted turtles. They constructed a 0.6 m x 0.6 m x 6 m long tunnel connected to 40 m of drift fencing on either side and placed it between a wetland and an upland nesting area. Their study tested the response of female painted turtles that encountered the simulated underpass as they moved to upland areas to nest. They recorded the number of turtles that successfully reached the tunnel, number of turtles that successfully passed through the tunnel, and the amount of time each turtle took to pass through the tunnel. Turtles were observed on 35 occasions as they encountered the drift fences and tunnel. Turtles successfully reached the tunnel 20 of the 35 encounters, of which, all successfully passed through it. The mean time to transverse the tunnel was 113 seconds (median 120; range 60-197). They inferred that a 0.6 m x 0.6 m x 6 m long underpass may be acceptable to successfully pass painted turtles.

Griffin (2005) wanted to determine if aluminum flashing at the top of wire fence would be sufficient to stop western painted turtles (*Chrysemys picta belli*) from climbing over barrier fencing. The objective was to identify a low cost alternative barrier and directional fencing. They conducted enclosure trials that were moved to various ponds in Mission Valley, Montana. There were a total of 8 circular enclosures built with 2.5 cm x 5 cm welded wire, 61 cm in diameter and 45.7 in height. On the inside of each enclosure there was either 10 cm or 15 cm of aluminum flashing that was attached flush with the top of the enclosure. Two turtles were randomly assigned to each pen for the course of the 1 hour trial. Only 4 of the 124 turtles were able to climb the flashing. Griffin (2005) inferred that it was unlikely that the majority of turtles, if any, could breech fencing that had aluminum fencing attached.

Woltz et al. (2008) is the only published study that examined how aperture diameter (0.3 m, 0.5 m, 0.6 m, and 0.8 m), substrate type (concrete, soil, gravel, and PVC), length (3.0 m, 6.1 m, and 9.1 m), and light permeability (0%, 0.65%, 1.3%, and 4.0%) influence the preference of turtles for crossing structures. They constructed a series of behavioral choice arenas to test the responses of painted turtles and snapping turtles (*Chelydra serpentina*) to guide fences and tunnels. Arenas consisted of 4 different exit options that radiated out as the only points of egress from a central starting enclosure. The observer exposed the individual to the trial for 15 minutes. If an animal had not exited the central enclosure after 15 minutes, a choice of no decision was made. Woltz et al. (2008) recommend that a tunnel with a diameter of 0.5 m or greater diameter, lined with soil or gravel and accompanied by a 0.6-0.9 m high guide fence would best facilitate road crossings for turtles.

Designing solutions to transportation-based conflicts with wildlife is complex. To do it effectively requires research evaluating responses of a number of species to a variety of passage features (Jochimsen et al. 2004). Understanding how the structural design (dimension, position, lighting, and substrate) of these systems affects the willingness of turtles to use them, will allow for better design of turtle passages (Woltz et al. 2008).

The goal of our study was to examine the relative effectiveness of experimental passages for freshwater turtles in Massachusetts. This study attempted to address the design characteristics of passage structure size and position relative to the road and surrounding landscape. Structures were evaluated with respect to how their height, width, and position (at or below-grade), influenced the movements of painted turtles. We predicted that turtles would respond better to passage structures with the largest dimensions and would prefer tunnels at-grade. We measured the effectiveness of passage structures on a relative scale using painted turtles. This measure allowed us to test several design variables on a large number of turtles; something that is very difficult to conduct in the wild. Painted turtles were selected as a study species because they are relatively common in Massachusetts and yet are still affected by roads (Fowle 1996, Baldwin et al. 2004, Marchand & Litvaitis 2004, Steen & Gibbs 2004). In addition, painted turtles have served as a study species in several previous behavioral experiments (Jackson & Marchand 1998, Griffin 2005, Woltz et al. 2008).

Methods

Experimental Design

A factorial design was used to experimentally test tunnel size and position on the passage of painted turtles. The experimental variables were tunnel size, tunnel position, and their interaction. There were 3 size treatments (0.6 m x 0.6 m, 0.6 m x 1.2 m, and 1.2 m x 1.2 m) that were crossed with 2 positional treatments (at and below-grade). Tunnel sizes were selected based on the design recommendations found in the scientific literature (Jackson 2003, Woltz et al. 2008). We decided to run single trials versus a choice experiment because: (1) site limitations: a choice experiment would only allow us to test 4 different tunnels at any given time, leading to a reduction in the number of tunnel sizes that we could have tested; (2) logistical constraints: With a choice experiment we could not have randomized tunnel start direction. We would have had to physically move each of the tunnels to another compass direction (not feasible with our tunnels, especially the ones below-grade); (3) experimental constraints: it would be difficult for us to compare each tunnel to each of the others, while maintaining a large and equal sample size. Turtles were randomly and evenly distributed across the six treatments to ensure a balanced study.

We assessed the turtle's reactions to the experimental trials using 3 main response variables: (1) Total time to complete trial; (2) Total hesitations observed; (3) Success, defined as no hesitations and completion of the trial. Total time to complete trial was the time from the start of the trial to either the turtle exiting the tunnel, or when the trial reached its allowed completion time of 120 minutes. Turtles that exited the tunnel in under 120 minutes were considered to have completed the trial. Total hesitations observed was the total number of hesitations consisting of three distinct behaviors considered collectively: (1) Bypass- a turtle walked past the entrance of a tunnel without stopping; (2) Approach- a turtle walked up to the entrance, stopped, and then immediately turned around; (3) False start- a turtle entered the tunnel, and then returned back through the tunnel entrance without completing the trial. Success was defined as having no hesitations and completion of the trial in less than 120 minutes.

Evaluating the experimental factors of size and position using three response variables allowed us to better understand the behavioral responses of painted turtles. Each response measured the performance of a turtle at a different level. The least conservative measure was total time to complete trial because it measured the ability of a turtle to complete the trial in less than 120 minutes, and it did not consider behavioral hesitations as a deterrent to passage use. A turtle may hesitate at the opening of tunnel and ultimately choose to quickly pass through a tunnel. The most conservative measure of success was that based on zero hesitations and completion of the trial in less than 120 minutes. This response variable assumed that a single hesitation would in real-life application result in a turtle's decision not to use the tunnel. Our rationale was to account for the limiting factor of pen size as compared to real life situations in which a turtle could travel for many meters in either direction and choose to pass or else turn away because of a single hesitation.

We also recorded additional covariates to determine if they affected the performance of the turtles in the experimental trials, relative to the experimental variables. These additional predictor variables were classified as categorical or continuous. Categorical variables included: (1) Weather (Clear, Partly cloudy, Mostly cloudy, Overcast, Light rain, Heavy rain); (2) Age (Juvenile, Adult); (3) Sex (Male, Female, Unknown); (4) Gravid (Yes, No, Unknown); (5) Tunnel start direction (North, South). Continuous: (1) Carapace length (mm); (2) Carapace width (mm); (3) Weight (g); (4) Temperature (C); (5) Start time (time of day).

Experimental Field Laboratory

The study site was located on the Tilson Farm facility of the University of Massachusetts Amherst. The site was selected because it was easily accessible, located in close proximity to local populations of painted turtles, had ample storage space and provided us with the required electrical and water utilities.

All experimental trial designs consisted of a 12.2 m long tunnel, rectangular in cross-section with a closed top. Tunnel size and position varied depending on the experimental trial. Tunnels were placed in a standardized north-south orientation. The sides and top of the tunnels consisted of plywood attached to wooden supports. The floor of the tunnels consisted of soil at the site. The below-grade tunnels were constructed in excavated trenches to simulate embedded tunnels. The pens of the below-grade tunnels had a standardized 33% slope down to the opening of the tunnels.

Enclosures attached on either end of the tunnels served as standardized start or exit pens for the trials. They were circular and had open tops (4.6 m small diameter and 6.1 m large diameter) (Figure 3). The pen fencing was constructed of 0.9 m high rabbit fencing covered with landscape fabric. The fencing blocked most potential visual stressors and distractions from the surrounding environment. No food, water or shelter were present inside the pens to ensure that turtles had some motivation for leaving the pen. The flooring of the pens was raked daily in order to remove vegetation and disrupt or eliminate any chemical trails left by turtles that were tested previously.

Turtles were trapped within a 16 km radius of the University of Massachusetts Amherst. They were captured using hoop nets and large minnow traps. Traps were baited with sardines packed in soybean oil. Trapping began in May of 2007 and continued through June of 2007. Traps were set and checked in the early morning. Bait was replaced on alternating days. Captured turtles were removed from the traps, checked for previous shell notches and then transported to the experimental field site. Turtles were transported in 45 liter coolers to minimize the adverse affects of stress.

On days when trials were not being run, traps were either removed from the wetlands, or not set. We assumed that every turtle taken back to the field site for analysis had no previous experiences with behavioral testing. Each turtle captured was marked by notching with a unique identification number (Ernst et al. 1974), after they have been exposed to the behavioral trials, to ensure that individuals were not used for multiple trials.

Behavioral Trials

Wild-caught turtles were brought to the field laboratory and given a unique identification number. This number was taped to their carapace throughout the trials for identification purposes. Turtles were randomly assigned to one of the six experimental tunnels. The start direction of each tunnel was also randomly assigned (north or south). Random selection of the tunnels and their start direction allowed us to control for researcher and directional bias. The random selection of tunnels and pens were facilitated using a Microsoft Excel 2003 spreadsheet.

At the beginning of a trial a turtle was placed in the start pen of one of the six experimental tunnels. Once a turtle was placed in the start pen, it was given 120 minutes to complete the trial. Completion of the trial was defined as a turtle moving from the start pen through the tunnel and into the exit pen. Once a turtle had reached the exit pen or exceeded the 120 minute time limit, it was removed from the trial. If a turtle did not successfully complete the trial, it was given a maximum time score of 120 minutes.

Behavior of the turtles in the start pen were recorded using a Pclix LT 100 time-lapse trigger and Canon Powershot G2 digital camera. The camera was elevated above the start pen and took a picture every 5 seconds for the duration of the trial. Heath-Zenith 6030 motion sensors were placed at the exit end of the tunnels to determine completion of the trials.

Following a turtle's exposure to a trial, their individual information was recorded (age, sex, whether or not they were gravid, maximum carapace length, maximum carapace width, and weight). The carapace was notched using the Ernst et al. (1974) notch code system. The notch code number was the turtle's identification number for the experimental trial. At the end of a day of trials, all turtles were released at their point of capture. They were never used for more than one trial.

All equipment that came into contact with the study animals was sanitized using a 10% bleach solution wash, a detergent soak, freshwater rinse, and allowed to sun dry. This was to minimize the possibility of spreading pathogens among wetlands.

Behavioral Analysis

Total time to complete a trial was the time from the start of the trial to either the turtle exiting the tunnel, or when the trial reached its allowed completion time of 120 minutes. Turtles that exited the tunnel in under 120 minutes were considered to have successfully completed the trial. This response was recorded in minutes and confirmed by comparing the start time and end time of each trial. A 2-factor analysis of variance (ANOVA) was used as the statistical model.

Total hesitation was the pooled number of bypasses, approaches, and false starts observed during the trial. These data were collected by analyzing the time-lapse photos generated from the camera positioned in the start pen. A 2-factor ANOVA was used to model the total number of hesitations observed in the trial. The data were cube-root transformed before analysis in order to meet all statistical assumptions.

Success was derived by using subsets of the total time and hesitations data. A log linear model was used for statistical analysis. Data were managed in a Microsoft Excel 2003 Spreadsheet. All statistical analyses were conducted using JMPIN 4.0.4. An alpha level of 0.05 was set for all statistical tests.

Results

One hundred ninety painted turtles were used in the trials from 16 May to 21 June 2007 (Table 4). Of these 190 turtles, 149 completed the trial in less than 120 minutes (Table 5). Ten of the 41 that did not successfully complete the trial, also never left the start pen (Table 5).

Total Time to Complete Trial

All 190 turtles were included in the total time to complete the trial so as to maintain a similar sample sizes for each of the trials. Turtles that did not successfully complete the trial were given a maximum time score of 120 minutes. The 2-factor ANOVA for total time to complete trial yielded the following results: tunnel size (D.F. =2; $F = 0.008$; $P < 0.05$), tunnel position (D.F. =1; $F = 0.3$; $P < 0.05$), and the interaction between tunnel size and position (D.F. =2; $F = 0.01$; $P < 0.05$). The ANOVA indicated that that tunnel size and the interaction of tunnel size and position are significant predictors.

The median (SD) times to complete the trials with all 190 turtle were calculated (Table 6). An interaction plot illustrates the interaction between size and position for the mean total times to complete trial (Figure 4). The interaction between size and position appears to be driven by the 0.6 m x 0.6 m tunnel size when it is at and below-grade. We also looked at the total times to complete trial for only those turtles that successfully completed the trial in less than 120 minutes (149/190; Table 7). The mean (SD) total times for turtles that completed the trial total times were identified (Table 8).

Total Hesitations Observed

The 2-factor ANOVA for total hesitations observed in the trials yielded the following results: tunnel size (D.F. =2; F = 0.003; $P < 0.05$), tunnel position (D.F. =1; F = 0.02; $P < 0.05$), and the interaction between tunnel size and position (D.F. =2; F = 0.4; $P < 0.05$). The ANOVA indicated that that tunnel size and position are both significant predictors. The untransformed mean (SD) number of hesitations observed in the trials were calculated (Table 9).

Success

Ninety-seven of the 190 turtles exposed to the trials exhibited 0 hesitations and completed the trial in less than 120 minutes (Table 10). The log linear model yielded the following results: tunnel size (D.F. =2; ChiSq = 0.01; $P < 0.05$), tunnel position (D.F. =1; ChiSq = 0.2; $P < 0.05$), and the interaction between tunnel size and position (D.F. =2; ChiSq = 0.03; $P < 0.05$). The log linear model indicated that tunnel size and the interaction of tunnel size and position are significant predictors.

We also calculated the percent success of the trials based on the number of turtles that exhibited zero hesitations and completed the trial in less than 120 minutes. The percent success based on the number of turtles that exhibited no hesitations and successfully completed the trial were calculated (Table 11). The percent successes were graphed into an interaction plot. The interaction between size and position appears to be driven by the 0.6 m x 0.6 m tunnel size when it is at and below-grade (Figure 5).

Additional Predictor Variables

None of the additional categorical or continuous variables were significant predictors in relative terms to tunnel size, position, and the size x position interaction. The mean, standard deviation and range were recorded for all continuous variables (Mean (SD); Range): Carapace length (mm) = (130.7(20.7); 66.6-180.6); Carapace width (mm) = (97.2(13); 31.6-120.2); Weight (g) = (296.2 (120.3); 30-610); Temperature (C) = (24.5 (4.5); 11-34); Start time (min.) = (12:28pm(0.06); 9:21am-5:05pm). The total counts were recorded for all categorical variables: Weather = (Clear: 108; Partly cloudy: 44; Mostly cloudy: 16; Overcast: 14; Light rain: 5; Heavy rain: 3); Age = (Adult: 171; Juvenile: 19); Sex = (Male: 93; Female: 76; Unknown: 21); Gravid = (Yes: 26; No: 145; Unknown: 19); Tunnel start direction = (North: 90; South: 100).

Discussion

We attempted to address the concerns of how tunnel size and position affect the relative effectiveness of road passage structures for freshwater turtles. Structures were evaluated with respect to how their height, width, and position (at or below-grade), influenced the movement behavior of painted turtles. A total of 190 turtles were exposed to the experiential trials and their behavior was characterized by 3 response variables (Total time to complete the trial, Total hesitations observed, and Success based on no hesitations and completion of the trial in less than 120 minutes). All three of these responses are a relative measure of effectiveness. These are relative measures because we are making the assumption that the behavior observed in the trials translates to the actual preference of tunnel size and position of freshwater turtles in the wild.

Total Time to Complete Trial

The ANOVA indicated that tunnel size and the interaction of tunnel size and position were both significant predictors. When analyzing the median total time to complete trial for all 190 turtles we found that as the size of below-grade tunnels increases the median time decreases ((0.6 m x 0.6 m) = 84 min; (0.6 m x 1.2 m) = 58 min; (1.2 m x 1.2 m) = 19 min). This is not the case with the at-grade tunnels. The median time for the at-grade tunnels remains relatively constant when comparing the sizes of 0.6 m x 0.6 m and 1.2 m x 1.2 m; however, the median time of the 0.6 m x 1.2 m at-grade tunnel was 60 min. We are unsure of the reason for this. One possibility is that the patchy vegetation in this tunnel delayed the movement of the turtles. This tunnel was the only one that had a vegetation problem.

We were also interested in the mean total times of the trial with only turtles that completed the trial in less than 120 minutes considered (149/190). This allowed us to look at the successful mean time for turtles that exited through the tunnel. There was no obvious trend observed in these mean values. The totaled mean time for at-grade tunnels had a lower mean value than the below-grade tunnels. There was also no obvious trend in tunnel size. Only 10 of the 190 turtles never left the start pen. This statistic indicates that the escape response was enough of a motivation to leave the start pen.

Total Hesitations Observed

The ANOVA for the total hesitations observed indicated that tunnel size and position were significant predictors. The untransformed mean total hesitations for the 6 trials suggest that the at-grade tunnels had fewer hesitations observed compared to the below-grade tunnels. Tunnel size does not appear to follow a similar trend. Overall, the 1.2 m x 1.2 m tunnels (at-grade) = 0.9; (below-grade) = 1.2) did have the lowest mean hesitations; however, the 0.6 m x 0.6 m tunnels ((at-grade) = 1.7; (below-grade) = 2.4) did not have the largest mean number of hesitations.

Success

This was the third and final response. It was also the most conservative definition of success. A turtle had to show no hesitation and exit through the tunnel to be considered successful (97/190). The log linear model indicated that tunnel size and the interaction of tunnel size and position were both significant predictors. The percent success generated for each of the trials indicated that as the tunnel size of below-grade tunnels increased, the success rate increased. The success rate for tunnel size did not show a similar trend. The totaled success for at-grade tunnels had a slightly higher rate of success than the below-grade tunnels (56% and 46%, respectively).

Additional Predictors

The purpose of tracking the additional predictors was to identify any potentially confounding factors. We were able to control the structural and experimental design of the study; however environmental (temperature and weather) and biological conditions (age, sex, gravid, and body size) could not be controlled. We made the assumption that within our study period (16 May – 21 June 2007), every turtle had an equal opportunity to complete the trials. We also wanted to control for compass direction, and therefore randomly assigned the tunnel start direction daily to control for this. There was no preference for direction by the painted turtles in the study. Woltz et al 2008 also reported this observation in their study. None of the additional variables (weather, age, sex, gravid, tunnel start direction, carapace length, carapace width, weight, temperature, and start time) were significant predictors to the models relative to tunnel size, position, and the size x position interaction.

Conclusions

All three of the responses indicated that tunnel size was a significant predictor. Total time to complete trial and success based on no hesitations indicated that the interaction between tunnel size and position was also a significant predictor. Only total hesitations observed identified position as a significant predictor. When looking at tunnel size, the largest size tested (1.2 m x 1.2 m) had the fewest turtles that never left the start pen, lowest total time to complete trial, fewest hesitations observed, and the highest success rate based on no hesitations and successful completion of the trials in less than 120 minutes. This was not always the case when looking at the other two sizes (0.6 m x 0.6 m and 0.6 m x 1.2 m). The 0.6 m x 1.2 m tunnel size had a higher total time to complete trial, more hesitations, and a lower success rate than 0.6 m x 0.6 m or 1.2 m x 1.2 m. This may have been affected by the 0.6 m x 1.2 m at-grade tunnel with the vegetation problem.

Tunnel position was identified by total hesitations observed as a significant predictor; however, this is not clearly represented when looking at the individual experimental trials. When at-grade trials were combined, they indicate relatively lower total times to complete trial, less hesitations observed, higher success rate based on no hesitations and successful completion of the trial in less than 120 minutes than the below-grade position. At-grade tunnels also had only a single turtle that never left the start pen.

When comparing at-grade and below-grade tunnels at the different size levels this was not always true. This may lead back to the 0.6 m x 1.2 m tunnel size and potential vegetation issue. There was a visible trend when looking at the interaction between tunnel size and position, specifically at the below-grade position. As the size of the below-grade tunnels increased the total time to complete trial decreased, fewer hesitations were observed, and the success rate increased. The number of turtles that never left the start pen also decreased.

We conclude that painted turtles exposed to below-grade tunnels were less hesitant and traveled faster through them as the tunnel size increased from 0.6 m x 0.6 m to 1.2 m x 1.2 m. The 1.2 m x 1.2 m tunnel size overall proved to be the size with the fewest hesitations observed, fastest total times, and highest success rate.

Limitations

There were two types of limitations associated with this study, design and site. The major design limitation was the ability to only measure the relative effectiveness of experimental passage structures. This is because we conducted our research in an outdoor laboratory away from the natural habitat of painted turtles. We felt the ability to rapidly modify and control the experimental trials outweighed the benefits of working in the natural habitat. Logistically, this type of study would be difficult to implement in a natural system. At the field laboratory we constructed the tunnels to represent the realistic length of 2-lane roads.

The Tilson Farm facility of the University of Massachusetts Amherst provided us with all of the logistics needed to implement this study; however, there was only a limited amount of space available. As a result the compass direction and pen size had to be fixed. The trials were orientated in a north to south direction, which allowed us to randomly start turtles in a south or north facing direction. We wanted to provide the turtles with the most amount of space possible to make their decisions about the tunnels. This was limited by the space on the property. One concern with standardizing all of the pens is the difference in the amount of level surface found between at-grade and below-grade tunnels. The amount of level surface among the different sized below-grade tunnels varied because of the standardize slope in the pens. When the tunnel size increased for the below-grade tunnels, the amount of level surface area in the pens decreased. It is difficult to standardize every component of a study, especially when one of the treatments is position. We accepted this limitation and made the assumption that it did not affect turtle performance.

We wanted to maximize the turtle's exposure time to the tunnels, while still being able to reach the sample sizes needed for the study. Woltz et al (2008) noted that one of their limitations was the length of their trials periods. They suspected that balking rates would diminish, and patterns of selectivity would be more resolved, if animals were provided more time. On the other hand we were unable to conduct 18-hour trial periods as in the long term experiments of Ruby et al. (1995). The 2-hour trial period was selected as a compromise between turtle exposure time and sample size.

We only tested wild caught turtles that have never been used in previous trial studies. In doing that we assumed that every unmarked turtle had never been exposed to behavioral study and that their motivation was the same when exposed to the trials. We also made the assumption that a turtle's motivation to leave the start pen was to escape unfavorable conditions. The calculated responses and results of the study can only be assessed in relative terms because we are assuming that the behaviors observed in the study are similar to what would be documented under natural conditions. Knowledge of the local landscape and population are still helpful for assessing the potential effectiveness of these structures at the local level.

Several challenges arose during the course of this study. The 0.6 m x 1.2 m at-grade tunnel required constant maintenance to remove patchy grasses and weeds from inside the tunnel. The size of the tunnel made it difficult to work inside of it to remove such vegetation. The motion sensor at the exit of the trials also proved to be not as reliable as we hoped. This required us, at times, to check on the trials to ensure accuracy. To eliminate this problem of the presence of researchers in the trial area; one could use security cameras or other direct feed cameras to an area where research can safely be observed.

Management Implications

Most tunnel design recommendations come from published literature reviews or monitoring of existing road culverts. These studies defend their recommendations by direct and indirect evidence of tunnel use. Cavallaro et al. (2005) have stated that the minimum tunnel height for amphibians and reptiles should be at least 0.3 m. Others recommend that small rectangular box culverts (e.g. 0.6 m x 0.6 m) should be used wherever roadways pass along the boundary of uplands and wetlands (Jackson & Griffin 2000). A study in Florida evaluated the effectiveness of existing barrier walls and culverts, and documented that freshwater turtles use culverts that were 2.4 m x 2.4 m and 0.9 m x 0.9 m in size (Dodd et al. 2004). Another Florida study documented the use of a 3.5 m diameter culvert by turtles (Aresco 2005). Over 2 years of tracking, he recorded more than 200 turtles using the culvert (Aresco 2005). A study in Massachusetts monitored the use of a 1.8 m x 1.8 m culvert by spotted turtles (Kaye et al. 2005). They confirmed tunnel use by radio telemetry, thread tracking, and visual observations (Kaye et al. 2005). Finally, a study conducted for the Florida Department of Transportation, monitored wildlife use of culverts and attempted to generate design recommendations based on these findings (Smith 2003). They recommend that the best culvert design for reptiles and amphibians is a passage with a height less than 1.5 m and width greater than 2.7 m (Smith 2003). Hagood & Bartles documented the use of a 0.5 m drainage culvert by 3 eastern box turtles. All of these findings provide us with well documented case studies of tunnel use; however, they do not assess the influence that structural design variables, such as tunnel position, lighting and dimensions have on individual tunnel design elements.

Woltz et al. (2008) is the only published study that assesses road crossing structure design through experimental analysis. They tested 74 painted turtles as well as 62 snapping turtles in their study to determine the specific features (aperture diameter, substrate type, length, and light permeability) that are important to turtles. Turtles were placed in an arena and given 15 minutes to choose one of four experimental tunnels to exit through it. If they did not exit the arena in 15 minutes, they were considered to have a choice of no decision. Their results indicate that painted turtles preferred tunnels of intermediate size (0.5 m – 0.6 m) and that snapping turtles preferred the larger diameter (>0.5 m) tunnels that they tested (Woltz et al. 2008). They recommend that a tunnel with a diameter of 0.5 m or greater lined with soil or gravel and accompanied by a 0.6-0.9 m high guide fence would best facilitate road crossings for turtles (Woltz et al. 2008).

We were able improve our study by understanding the limitations and challenges identified by Woltz et al. (2008). They stated that they had constraints that limited their ability to test larger dimension passage structures, tunnel lengths, and the amount of time they could allot for trial periods. We were able to test a tunnel length that mimics the width of 2 lane roads. In addition, we were able to test the response of turtles to box-culvert style structures as well as test larger sizes (0.6 m x 1.2 m and 1.2 m x 1.2 m). We used a trial period of 120 minutes in response to the concerns regarding the trial period by Woltz et al. (2008).

Woltz et al. (2008) did not uniquely mark turtles after release from their experimental trials. By not identifying turtles that have been exposed to the experimental trials, it potentially introduces pseudo-replication into their results. They cannot confirm that they have exposed 74 different painted turtles to their analysis. Exposing a turtle to more than one trial also introduces the potential confounding factor of learned behavior. We eliminated these concerns by only exposing turtles to only a single trial and systematically notching each individual prior to release.

Based on the results of our study and the information currently available in the scientific literature, we can make passage design recommendations. Our study indicated that turtles were more hesitant to enter tunnels that were below-grade and moved more slowly through these tunnels. In addition, the 1.2 m x 1.2 m tunnel size overall proved to be the size with the fewest hesitations observed, fastest total times, and highest success rate. We would recommend this tunnel size as an estimate for a minimum tunnel size for crossing structures designed for turtles. This is similar to the size recommendation of Woltz et al. (2008) because they suggested the aperture of the crossing to be at least 0.5

m in diameter. Multiple field studies have documented the use of passage structures that were as large as 0.9 m in size (Smith 2003, Dodd et al. 2004, Aresco 2005, Kaye et al. 2005). Combing the observation recorded from field studies and the relative results obtained from experimental trials, we conclude that the minimum size of passage structures for turtles should be 1.2 m. Future designs should be considered adaptive and additional research should be conducted to further identify the components of an effective passage structure.

Future Research

Future studies of the behavior of turtles in response to experimental crossing structures should consider the use of security cameras or forms of remote monitoring to reduce the potential effects of human presence in the study area; since human activity can influence the success of passage structures (Yanes et al. 1995, Jackson & Marchand 1998, Clevenger & Waltho 2000). Determining the most appropriate trial period can be difficult, due to limitations outside of the study design. It is thought that success rates would increase, and patterns of selectivity would be more resolved, if animals were provided more time (Woltz et al 2008). When breaking down the trial period into 30 minute intervals, it was noted that the success rate for turtles completing the trials under the allotted time decreased as the trial period was reduced ((120) = 78%; (90) = 72%; (60) = 65 %; (30) = 47%). The overall success rate dropped below 50% at the 30 minute interval. The success rate did not change drastically between the 120 minute and 60 minute trial period. This observation does provide evidence that supports Woltz et al (2008) idea of performance over time. Ultimately, the trial period will be determined by the ability of the researchers to conduct the study; however this may better represent the trade-offs associated with selecting a trial period shorter than 120 minutes.

There is still the need to understand the effects that roads have on turtles as well as to identify the factors that limit their use of road passage structures. Our findings suggest that 1.2 m x 1.2 m tunnels are the most effective size of those we tested. Larger tunnel heights and widths need to be evaluated because we have not identified an optimal design in which turtle behavioral responses indicate an obvious preference.

The effect of tunnel length and lighting also needs to be addressed. If lighting is the limiting factor, smaller tunnels with open top designs may be as effective as larger tunnels. Quantifying the ideal percent lighting in a passage structure will allow biologists to justify their lighting design recommendations to developers and governmental agencies. Smaller tunnel designs will reduce the cost of installation and serve as a solution for mitigation sites with water table and fill issues. A lower cost and biologically effective tunnel will allow these structures to be installed at a higher rate.

Fencing length and angle play a role in the success of a passage structure. Questions remain as to what is the best fencing angle to guide turtles into passage structures or how long will a turtle follow a fence before turning away? Answers to these questions will help to identify how far apart crossing structures should be to maximize use as well as to assist in designing the most effective passage systems to prevent turtles from crossing the road and to guide them to a passage structure.

A

B

Figure 3: Experimental tunnels and pens used in the evaluation of tunnel size and position on painted turtles. (**A**) Aerial view of experimental trial tunnels; (**B**) A 0.6 m x 1.2 m tunnel placed below-grade, and having an entrance pen with a 33% slope toward the tunnel.

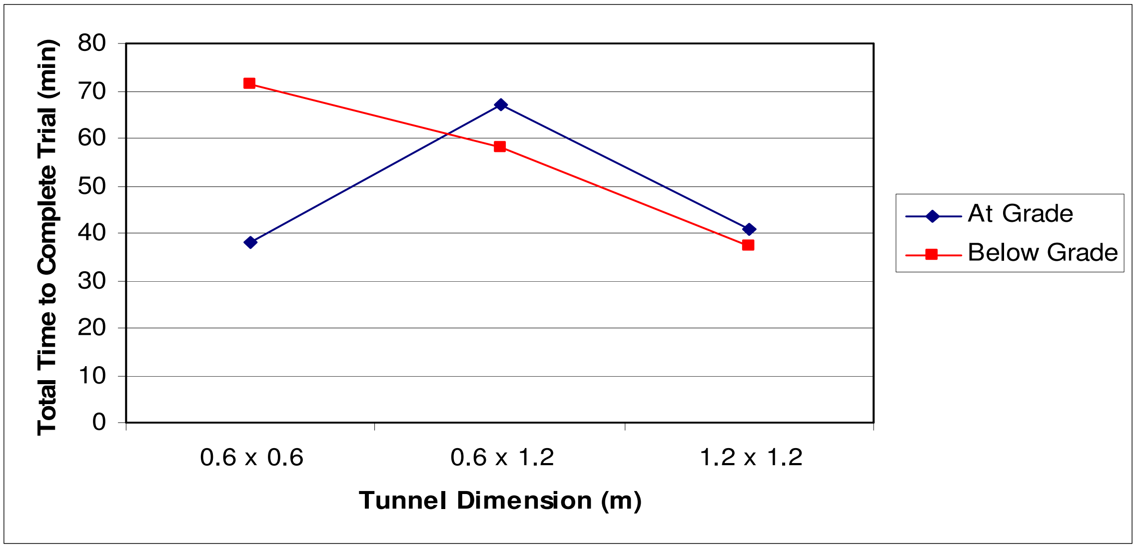


Figure 4: Interaction plot for the Mean total time to complete trial.

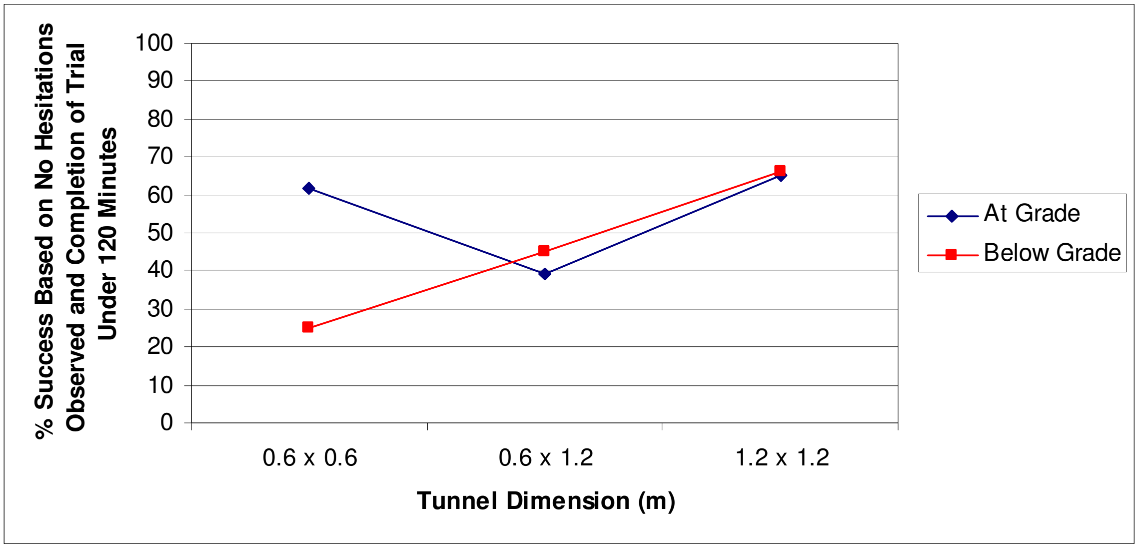


Figure 5: Interaction plot for the percent success based on no hesitations and completion of trial in less than 120 minutes.

Table 4: Experimental design. Number of turtles used in each treatment.

Tunnel Dimension Height (m) x Width (m)	Tunnel Position At-Grade	 Below-Grade
0.6 x 0.6	34	28
0.6 x 1.2	31	31
1.2 x 1.2	34	32

Table 5: Distribution of turtles that did not successfully complete the trial and never left the start pen.

Tunnel Dimension Height (m) x Width (m)	Tunnel Position At-Grade	Below-Grade
0.6 x 0.6	0	6
0.6 x 1.2	1	3
1.2 x 1.2	0	0

Table 6: The median (SD) times to complete the trials with all 190 turtle.

Tunnel Dimension	Tunnel Position	
Height (m) x Width (m)	At-Grade	Below-Grade
0.6 x 0.6	22.5 (37.8)	84 (48.4)
0.6 x 1.2	60 (51.3)	58 (44.3)
1.2 x 1.2	26 (39.0)	19 (39.9)

Table 7: Distribution of the 149 turtles that completed the trial in less than 120 minutes across the experimental design.

Tunnel Dimension Height (m) x Width (m)	Tunnel Position At-Grade	 Below-Grade
0.6 x 0.6	30	17
0.6 x 1.2	17	26
1.2 x 1.2	31	28

Table 8: The mean (SD) total times for turtles that completed the trial.

Tunnel Dimension	Tunnel Position	
Height (m) x Width (m)	At-Grade	Below-Grade
0.6 x 0.6	27.3 (24.1)	40.1 (35.8)
0.6 x 1.2	23.7 (22.2)	46.2 (38.0)
1.2 x 1.2	33.1 (31.4)	25.3 (25.7)

Table 9: The untransformed mean (SD) number of hesitations observed in the trials.

Tunnel Dimension	Tunnel Position	
Height (m) x Width (m)	At-Grade	Below-Grade
0.6 x 0.6	1.7 (1.8)	2.4 (2.7)
0.6 x 1.2	1.7 (1.9)	3.4 (3.3)
1.2 x 1.2	0.9 (1.3)	1.2 (1.5)

Table 10: Distribution of the 97 turtles that exhibited no hesitations and completed the trial in less than 120 minutes across the experimental design.

Tunnel Dimension	Tunnel Position	
Height (m) x Width (m)	At-Grade	Below-Grade
0.6 x 0.6	21	7
0.6 x 1.2	12	14
1.2 x 1.2	22	21

Table 11: Percent success based on the number of turtles that exhibited no hesitations and successfully completed the trial.

Tunnel Dimension Height (m) x Width (m)	Tunnel Position At-Grade	 Below-Grade
0.6 x 0.6	62%	25%
0.6 x 1.2	39%	45%
1.2 x 1.2	65%	66%

APPENDIX

MASSACHUSETTS TURTLE ROAD MITIGATION SYSTEMS

A B

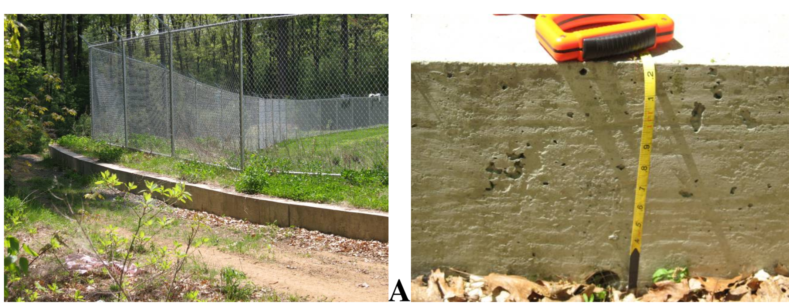
Carver, MA Site

A B

Groton, MA Site

A B

Taunton, MA Site



A B

Westfield, MA Site


A

B

Gill, MA Site


A


B

New Bedford, MA Site


A


B

Marshfield, MA Site


A


B

Wrentham, MA Site


A

B

Southampton, MA Site


A

B

Harvard, MA Site


A

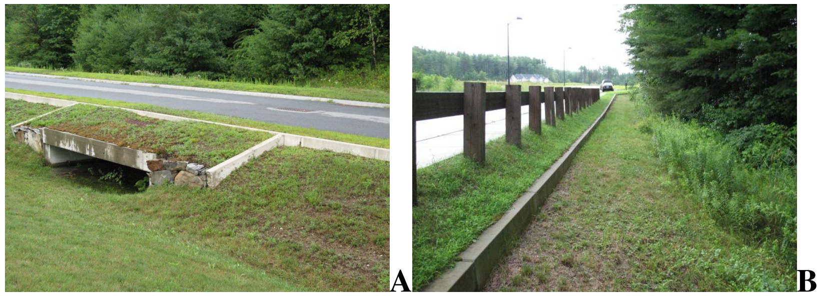
B

Westford, MA Site


A

B

Ayer, MA Site



Boxborough, MA Site

Hingham, MA Site

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